International Workshop on Vacuum Electron Devices

Informal Technical Report

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Date: November 12, 1997

Venue: Kharkov Technical University of Radio Electronics, Kharkov, Ukraine

Agenda: Six out of 7 announced in the program invited papers were presented by invited speakers from Kharkov (4), Kiev (1) and Moscow (1). One paper was withdrawn, by G.I. Sergeev (Moscow). At the poster session, three papers were presented. Abstracts and extended abstracts of the papers are enclosed.

Discussions: Those were focused mainly on the topics reviewed in the papers of E. D. Shlifer and V. D. Naumenko, as they might find potential customers in the industry. It was noted that although millimeter-wave magnetrons have not been in use for the high-frequency heating and drying, this might be a promising application. Microwave-pumped light emitters is a new technology that is not well-known yet for the customers. There is still a need of research on the optimal design and working regime of such sources and lighting systems.

There were no formal workshop conclusions made. It was admitted that the workshop had a success, however local response was lower than it could be. The crucial role of support from the workshop sponsors was acknowledged with gratitude.

A Nosich 03/02/98

Alexander I. Nosich
Workshop Int'l Liason
IEEE E. Ukraine Joint Chapter Secretary

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The Final Proceedings for 1997 International Workshop on Vacuum Electron Devices (IWVED '97), 12 November 1997 - 12 November 1997

The topics to be covered are electromagnetic field theory, millimeter-wave techniques, high-power electron devices, microwave industrial, scientific, and medical application.

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VACUUM ELECTRON DEVICES
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organized by
IEEE AP/MTT/ED/AES Societies East Ukraine Joint Chapter
in cooperation with
Academy of Sciences of Applied Radio Electronics
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Kharkov Technical University of Radio Electronics

Second Announcement and Final Program

One-day International Workshop on Vacuum Electron Devices (IWVED-97) will be held at the Kharkov Technical University of Radio Electronics, Kharkov, Ukraine, on November 12, 1997. Participation of leading experts in this field from Kharkov, Kiev, and Moscow is planned. In the program of the Workshop there are seven invited papers as follows:

8:10 - 8:50	V. I. Gomozov, *"Modulation of microwave tubes with electrical and electrodynamic control; theory and applications"*, Research and Development Institute "Radmir", Kharkov, Ukraine
9:00 - 9:40N.	I. Ayzatsky, *"Application of microwave sources in linear electron accelerators"*, Accelerator Institute, National Center "Kharkov Physical-Technical Institute", Kharkov, Ukraine
9:50 - 10:30	E. D. Shlifer, *"Pumping the discharge sources of optical radiation with microwaves"*, Pluton State Company, Moscow, Russia
10:40 - 11:20	V. I. Naidenko, *"O-type super-power multi-beam vacuum tubes: electrodynamic structures"*, Radio Engineering Department, Kiev Polytechnical Institute - Technical University, Kiev, Ukraine
11:30 - 12:10	G. I. Sergeev, *"Development of O-type traveling wave tubes in millimeter-wave range"*, Istok State Company, Fryazino, Russia
12:20 - 13:00	D. M. Vavriv, V. D. Naumenko, *"Research on cold-secondary-emission-cathode magnetrons"*, Institute of Radio Astronomy, National Academy of Sciences, Kharkov, Ukraine
13:10 - 13:50	V. D. Yeremka, *"Vacuum sources of millimeter waves on cyclotron frequency harmonics"*, Institute of Radiophysics and Electronics, National Academy of Sciences, Kharkov, Ukraine
14:00 - 16:00	Poster session

We wish to thank the following for the valuable contribution to the success of the Workshop:

- USAF European Office of Aerospace Research and Development
- European Research Office of USARDSG - UK

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Registration fee is not supposed. Workshop dinner will be arranged in the university cafeteria, the time to be announced at the meeting.

Dr. Gennadiy I. Churyumov, IWVED Organizer
Prof. Alexander I. Nosich, IEEE E.Ukraine Joint Chapter Secretary October 10, 1997

List of Participants
of the International Workshop on Vacuum Electron Devices

November 12, 1997, Kharkov Technical University of Radio Electronics

1. N. I. **Ayzatsky**, DSc, senior scientist, *Nat. Research Center - Kharkov Institute of Physics and Technology*
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20. I. V. **Ruzhentsev**, PhD, scientist, *Kharkov TU of Radio Electronics*
21. E. D. **Shlifer**, DSc, chief scientist, *"Pluton" State Co.*, Moscow, Russia
22. A. I. **Spitsyn**, PhD, lecturer, *Kharkov TU of Radio Electronics*
23. V. V. **Shcherbak**, PhD, scientist, *Inst. of Radiophysics and Electronics, National Academy of Sciences*, Kharkov
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31. G. I. **Zaginailov**, DSc, senior scientist, *Plasma Physics Dept., Kharkov State University*
32. V. A. **Zaporin**, prof., *Kharkov TU of Radio Electronics*
33. V. N. **Zinkovskii**, PhD student, *Kharkov TU of Radio Electronics*

Invited and poster paper abstracts

International Workshop on Vacuum Electron Devices

November 12, 1997
Kharkov Technical University of Radio Electronics

MODULATION OF MICROWAVE TUBES WITH ELECTRICAL AND ELECTRODYNAMIC CONTROL: THEORY AND APPLICATIONS

I. Gomozov
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In the paper, the foundations of the dynamic theory of angular modulation of oscillations. Unlike the conventional quasi-stationary theory, it takes into account non-stationary processes caused by the non-linearities of the frequency and phase characteristics, and by the inertial behavior of the microwave sources as control objects. Based on the proposed substitution schemes developed for such objects of control, by means of the method of given frequency and phase tuning and transient characteristics we have determined the dependences bɩ ·ɾeen dynamic input control voltages and the output signal frequency and phase. We introduce ɹasic concepts, define the essential points, and present the expressions for the dynamic tangent of the frequency or phase-tuning characteristics, dynamic index of the frequency or phase modulations; we also determine their analytical dependences on the corresponding traditional statistical characteristics widely used in conventional quasi-stationary theory of angular modulation of oscillations. Besides, we determine accurately the range of validity of quasi-stationary theory as a particular case of our problem, provided that one may neglect the inertial nature of the objects of modulation. Basic results for the modulation of the microwave sources with electric and electrodynamic control have been verified experimentally. We consider the principle of development of unified devices forming complicated signals with wide variation range of parameters, for the multi-functional radio and electronic systems. It is based on the usage, for the modulation, of microwave sources with electrical and dynamic control of the input control voltages of radio frequencies. Besides, we consider the specific features of usage of the mentioned types of microwave devices for the forming of such signals.

The paper is based on the following publications of the author:

1. V. I. Gomozov, Effect of the inertial character of the sources on the spectra of the frequency fluctuations in the noise modulation, Radioelectronics and Communic. Systems, no 11, pp. 64-70, 1977.
2. V. I. Gomozov, Analysis of the frequency modulation and auto-tuning devices accounting for the non-stationary processes in the sources, Sov. J. Communic. Technology Electron., vol. 23, no 4, pp. 760-770, 1978.
3. V. I. Gomozov, Chapter in Y. N. Sedyshev (Ed.), Receiving and Transmitting Devices of Radio Engineering Systems, Kharkov: VIRTA Press, pt. 1, pp. 245-255, 1991 (in Russian)

APPLICATION OF MICROWAVE SOURCES IN LINEAR ACCELERATORS OF ELECTRONS

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In this report we review the existing tubes (mainly klystrons) and discuss some specific problems in the connection of their using in electron linacs.In modern electron linacs, klystrons play an important role in the generation of RF power in the frequency range from a few hundred MHz to 15 GHz. The basic mechanism of generating RF power in a klystron consists of subjecting the dc electron beam emerging from a cathode to the RF field of an input cavity which is driven by an external low power RF generator. The resulting velocity modulation of the beam transforms into an intensity modulation by passing the beam through a drift tube. The output cavity which is located at the end of the drift space is exited by the RF component of the bunched beam. There are several areas of accelerating technology that are needy of new RF sources. First of all, these are electron colliders at 1 (or greater) TeV center-of-mass energy [1,2,3]. In order to maintain a reasonable overall length at high center-of-mass energy, the main linac of an electron-positron
linear collider must operate at a high accelerating gradient (30-100 MV/m). For conventional accelerator structures, this implies a high peak power per RF source. To provide this power, a number of devices are currently under active development or conceptual consideration:

- conventional *klystrons* with multi-cavity output structures. There are three X-band Linear Collider proposals which involve the development of new klystrons, namely NLC (SLAC), JLC (KEK), VLEPP (Novosibirsk, Protvino). The X-band Klystron Program at SLAC led to a development and successful testing a XL-4 klystron (f=11.4 GHz) for NLC [4,5]. This klystron has produced 50 MW at 1.5 (s) and 120 pps at the beam voltage of 400 kV with 43% efficiency; at a somewhat horter pulse width of 1.1 (s) it has reached 75 MW with efficiency of 48%. At KEK, a klystron is being developed in collaboration with Toshiba for X-band JLC collider. At the Protvino Branch of INF RAS, a prototype of a klystron for the VLEPP collider is being designed and tested. A novel feature of this klystron is a gridded gun, which enables the beam to be switched directly from a pulse-forming line without the need for high-voltage pulse modulator. A 150 MW S-band klystron for powering the DESY S-band linear collider (SBLC) has been designed and engineered at SLAC [6]. The design philosophy for these klystrons followed a conservative approach in which existing technology (that successfully was applied for SLAC 5045 klystron) was extended to higher beam currents and RF power densities.

- ***magnicons***

A magnicon is a scanning-beam microwave amplifier. It consists of a continuous electron beam which is deflected by the RF field of a circular deflection cavity [7]. In the subsequent drift space electrons deviate from the device axis and get into a stationary magnetic field of a solenoid. While entering the magnetic field the longitudinal velocity of the electrons is transformed into a rotational transverse one. Traveling along a helical trajectory in the output cavity, the electrons excite a TM110 oscillation mode. At the Budker Institute of Nuclear Physics, a 7 GHz magnicon has produced 30 MW at 35% efficiency. At the Naval Research Laboratory, an 11.4 GHz magnicon is under study with an output of 58 MW at 58% efficiency.

- ***gyroklystrons***

Gyroklystrons have extended annular beams and are capable to produce high RF power at high frequencies. The most extensive work on the development of high power gyroklystrons has taken place at the University of Maryland [8,9]. A gyroklystron is now under study which will eventually reach a simulated output power of 160 MW at 17.1 GHz with efficiency of 41%.

We must also mention the works in the field of RF pulse compression [1]. These systems can enhance the peak power output from a klystron by trading reduced pulsewidth for increased peak power. The first large scale pulse compression system for the accelerator application was the SLED scheme. A program has been in progress at SLAC to develop the SLED-II pulse compression system. This system is currently delivering an output power of about 150 MW, this power level is still increasing.

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6. D. Sprehn, G. Caryotakis, R.M. Phillips, 150-MW S-band Klystron Program at the Stanford Linear Accelerator Center. SLAC-PUB-7232, 1996.
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MICROWAVE PUMPING OF GAS DISCHARGE SOURCES OF OPTICAL RADIATION: PROBLEMS, TASKS AND DESIGN

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In September 1992, it was first reported about the creation of a new high-efficient source of light on the basis of microwave gas-discharge contact-free lamp. The report was presented by the specialists of the Fusion System Corporation (FSC) that had by then more than 20-year experience of developing and usage of industrial ultraviolet optical sources. In these sources, miniature (in particular, spherical) mercuric contact-free lamps with microwave pumping have been applied. In the 70-s the same FSC started testing of other (non-mercuric) filling substances that resulted in the development of so-called sulfur lamp radiating bright quasi-solar light. The company Fusion Lighting then separated from FSC and started intensive development and usage of sulfur contact-free lamps with microwave pumping (at a frequency of 2450 MHz).

Development and putting into operation two powerful (Pmw = 3.4 KW, light flux of 410 KL) illuminating systems with the sulfur lamp and the hollow prismatic light guides turned out to be the first successful step in this direction estimated as a technological "break-through" by the experts. Spectacular and pompous presentation of two similar lighting systems in Washington on October 20, 1994 (one in the National Museum of Astronautics and Aeronautics and another nearby the main Forrestol Building of the US Department of Energy) was actively commented by the mass media and attracted attention of scientists and engineers to a new and prospective technology. Fusion Lighting itself, owing to DOE $1.5 mln contract, created a less powerful sulfur lamp (Solar 1000; Pmw = 1 KW, light flux of 135 KL) and entered the international market with power-saving ecologically clean lighting systems. A comparison of the sulfur lamp and modern compact metal-halogen lamp characteristics has been published by G. N. Rokhlin, in the Journal of Light Technology, no 4, 1997 (in Russian). Microwave gas discharge sources of optical radiation are of significant interest for other applications as well. In particular, they can be used as radiators effecting "non-living" and "living" objects. Here, it is important to take into account the potentials of both the autonomous optical radiation effect on the object and the combined effect of optical and microwave radiation (including simultaneous, in-turn, and according to a programmed spatial-time variation). This is a poorly studied area by now. Nevertheless, one can note that not only ultraviolet radiators, but also combined ultraviolet + microwave ones are used already in industry for photo-biological installations of vital, photo-synthesis and bactericidal sort.

In Russia, sporadic poorly funded works on lighting the microwave discharge in spherical and other contact-free lamps with different (including argon-sulfur) fillings were started in 1995 by several R&D organizations. Steady interest to these works has been shown by the Academy of Electrical Engineering Sciences (AEES) of Russia.

A complex approach to the design of microwave-discharge contact-free sources of optical radiation in visible and ultraviolet (UV) spectral bands (light emitters and radiators), and systems of combined UV + microwave effect sources with magnetron pumping units has been realized at the Joint-Stock Company "Pluton" by our own initiative. In March 1996, we developed a working model of a light emitter realized as a searchlight based on the argon-sulfur lamp of visible radiation. In April 1997, an experimental bactericidal setup of combined UV + microwave effect on liquid flows and infected objects was built and tested. In July 1997, a lighting system containing a source of support power supply, microwave source and light-guiding section was developed. In a tight cooperation with scientists of several Moscow institutions, various fillings, types and

dimensions of burner, spectral and other characteristics have been studied. Also, the regimes of microwave pumping, different designs of elements and whole devices have been developed, and a number of new ideas have been elaborated. By now laboratory working models of the searchlight-type UV and UV + microwave bactericidal radiators based on the argon-mercuric spherical contact-free lamp with microwave pumping have been created. The systems are being developed currently for the local and developed systems of UV de-infecting of drinkable water and sewage, food products and various waste, for creating the vitalizing setups of medication, preventive and functionally-physiological action, for photo-synthesis radiators, and so on. In the course of all these works a lot of problems and difficulties revealed themselves. A part of them has been managed to overcome, whereas another part (perhaps, greater one) calls for considerable efforts.

In this review we shall try to group these problems into appropriate large blocks in order to inspire the specialists of different fields to enter the deve. ment of new light sources, radiators and complex devices. These problems can be grouped like to.lows:

a) Problems connected to a lamp (burner) itself, including
- A choice and optimization of structure and parameters of fillings, responsible for the ignition and steady work of the microwave discharge, for the character of the optical radiation spectrum and its keeping in the course of an operation,
- A choice of optimum shape and material of a burner flask.
- Determination and maintenance of a necessary temperature and its distribution around the flask surface in the stationary regime and in the regime of cooling down after switch off.

b) Problems connected with the system of microwave pumping, including
- A choice of power level and microwave signal form (continuous or amplitude-modulated).
- Provision of mechanism of effective transformation of microwave electromagnetic power to the optical radiation in all regimes of contact-free lamp operation from the starting to the stationary one.
- Development of microwave guides carrying the power from the source (magnetron) to the load (contact-free lamp) and devices ensuring (at a certain mode) a topography of the microwave field in the space of its interaction with the lamp working substance (in its initial state and in plasma one).
- Stability of magnetron operation with a load changing essentially in the course of microwave discharge progress (within the time interval from the start to the plasma stationary regime).
- A choice and realization of soft-type heating and electronic regimes of magnetron operation and maintenance of high reliability and long life-time (without significant degradation of parameters and failures).
- Development of microwave screening to prevent microwave pollution of environment and ensure ecological safety and electromagnetic compatibility (EMC) realized with a maximum or required transparency; acceptable thermal and shape stability of the screen and its air transparency.

c) Problems concerning the shaper of optical radiation beam, including
- A choice of reflector shape and dimensions taking into account separation or association of functions of optical shaper and microwave resonator.
- Providing the design compatibility between reflector and light distributing system, devices of lamp cooling and rotation, and in certain cases the irradiated objects.

d) Problems concerning the system of feeding, control (adjusting) and protection of the optical radiation source as a complex device, including

- A choice and optimization of the magnetron feeding voltage shape.
- Determination of objects to be protected and controlled, and of the type and character of physical factors, whose change the control (protection) system should react on.
- A choice of information messenger type, corresponding detectors and receivers of the control signal, converters of this signal into a command signal, and executive elements for a proper implementation of the control action.

e) Problems concerning the features of operation, including
- Providing stability with respect to external factors (climatic, mechanical) in the course of operation of the lamp itself and the whole device.
- Providing the operation with pre-selected and regulated combination of radiation types and additional effects (for example, ozone one) on the irradiated object.

f) Technological problems concerning design of the all listed in points a)-e) directions.

g) Problems related to the light-distributing system.

When creating devices of optical radiation using contact-free discharge lamps with microwave pumping, most of the named problems intertwine and cannot be overcome without a trade-off. Here we shall consider briefly only some examples.

For a quasi-solar optical light with reduced content of UV and infra-red (IR) we can consider as most suitable the following fillings of a burner: starting gas: either argon or neon, working medium: sulfur, selenium, and mixture of both plus different additions. For UV radiation sources: starting gas: argon, working medium: mercury.

When choosing fillers, one must take into account that chemical interaction with flask substance is not acceptable. Dehydrated quartz can be admitted as the best material for a flask.. Transparency for UV and visible radiation, chemical neutrality, capacity for work at high temperatures due to the absence of evaporating electrodes in the burner makes this lamp practically everlasting. At least under a condition that the heat and chemical stability of a cover at working values of temperature and pressure has been provided.

For operation in the searchlight radiators and lights with a given shape of the light flux (in particular, for feeding the optical fibers), a spherical shape of the flask should be admitted as the most attractive. Small dimensions of the flask and hence of the spherical luminescent space provide a possibility of its accurate orientation with respect to the reflector optical focus and with respect to the maximum of microwave pumping field intensity (for example, in the single-mode resonator).

For operation in irradiation chambers (multi-mode microwave resonators) it is preferable to make contact-free mercuric UV lamps of cylindrical shape (from quartz and UV-glass).

Over the block of problems concerning microwave pumping we can affirm the following.

For the lighting systems (in the visible part of spectrum) with the light flux oscillations of not more than 15 %, the non-amplitude-modulated microwave pumping field is preferable. The level of the microwave pumping power must be chosen depending on the required value of the output light flux (realistic value of the burner light output equals 130-150 Lm per 1 W of microwave power). Achievement of high efficiency of the microwave energy transformation to the energy of optical

radiation calls for finding out and realization of the microwave field optimum topography that in turn dictates the choice of the microwave resonator shape and oscillation mode. It is preferable to choose a single-mode resonator or a standing-wave transmission line, and to separate the functions of microwave resonator and optical flux shaper (reflector). This conclusion is valid mainly for searchlight sources. For the chamber-type UV + microwave installations a multimode operation of the microwave resonator (working chamber) makes a microwave field topography indefinite. In this situation it is necessary to provide as starting interaction of microwave power with buffer gas and working medium vapor in a passing wave with keeping the discharge by means of the joint action of resulting microwave fields. When using additional, so-called leaded contact-free, lamps the same needs an assisting action of UV radiation.

In order to provide a stable operation of the pumping magnetron in searchlight sources and radiators, where variable load is conditioned only by state of the contact-free lamp (pre-starting, starting and stationary), and in chamber-type installations of UV + microwave irradiation, where an irradiated object itself acts as a load as well, it is expedient to introduce additional fixed de-tuning elements into microwave circuit design. Their reactances and locations must restrict a range of reflectivity phase variation off the prohibited zone at the Riquet diagram. A trivial way is introduction of de-coupling non-reciprocal elements (isolators, circulators); but this is very heavy, expensive and causes additional loss.

In the light sources and searchlight UV radiators not purposed to a joint UV + microwave effect on the object, light-transparent microwave screen plays the role of a resonator wall as well. Depending on the chosen mode of oscillations, certain parts of this wall happen to be in the maxima of microwave currents that demands provision of reliable microwave contacts. Otherwise sparkles and local over-heating of the screen occur. In this case the products evaporating from the screen come to the burner quartz flask, and the flask transparency gets lost; in the worst case the screen is burnt through. This means that one has to use non-wicker nets as screens.

Among other problems not being directly among the workshop topics we shall point out only to the provision of reliability of complex devices based on contact-free discharge lamps with microwave pumping. We see this problem solution in the following measures:
- improving design reliability and life-time of the pumping magnetron to eliminate a frequent replacing the magnetron during the radiation source life-time (several tens of thousands hours).
- realization of gentler heat and electrical operating regimes and appropriate means of protection.

In conclusion I would like to note that perspectives of the use of various sources of optical radiation and UV + microwave radiation on the basis of microwave gas-discharge contact-free lamps (in the different parts of spectrum) are considered to be rather wide. Interest to such sources from the not accustomed consumers is registered after the first experience of using. I believe that the works on development of various modifications of light sources and systems should be intensified.

O-Type Super-Power Multi-Beam Vacuum Tubes: Electrodynamic Structures

V.I. Naidenko

Always there is a need of power and super-power devices [1,2]. These devices can be used in the thermo-nuclear synthesis, charged particle accelerators, space-solar electric power stations, industrial power equipment, HF-tactical weapon etc. The possible ways to increase the power can be seen from the following formula:

$$P=\eta I_o U_o$$

where η is the efficiency, *Io, Uo* are the current and voltage of the device.

The voltage increase should be avoided by many reasons such as: increase of the weigh and size of the device and power supply, X-ray radiation.

The increase of the efficiency, which is important itself, does not allow increasing the power significantly because the efficiency of the novel power devices is relatively high.

Thus we have the only possible way to increase the power: to increase the current. Direct increase of the current means a perveance increase of and an efficiency decrease due to the increase of the Coloumb force effect. To reduce the Coloumb forces a beam is divided into several sub-beams (multi-beam devices). However, this procedure does not allow one to increase the power considerably as the total current can be increased insignificantly. Besides, as a result of the use of a most part of an electrodynamic system cross-section for a sub-beam allocation, the effectiveness of interaction of sub-beams allocated far from the electric field maximum drops.

Below another approach is discussed. It is based on the use of space-developed electrodynamic systems. Devices using such systems are called "space-developed devices" (SDED).

More exactly, SDED's are the devices in the electrodynamic systems of which at least in one of cross-directions several halfwaves can be allocated. One can also think that electrodynamic systems of SDED are formed by means of a reproduction of a usual electrodynamic system along one or both cross-coordinates and of a choice of an appropriate phase shift between fields in neighbor compartments (cells).

It is expected that SDED will allow increasing the power level on 1-3 orders, decreasing the accelerating voltage, prolonging a lifetime, etc.

The confirmation of these expectations can be found in lasers, in which working body (beam) has cross-sizes considerably exceeding a wavelength. Electrodynamic systems of multi-beam devices (in particular with a system of connected ring resonators), devices with a band beam and gyrotrons are not space-developed in this meaning. When designing SDED some problems arise. We consider just one of them: the problem of design of space-developed electrodynamic system. The electrodynamic systems of SDED have to satisfy both traditional and new requirements: the band; coupling resistance; spectrum of oscillation types; small-perturbation stability; rigidity and strength; a distance between beams; amplitude-phase distribution at an exciter output; phasing of fields in each compartment (cell); thermo-dissipation ability, etc.

Some of the traditional requirements are weakened in SDED, while others are strengthened. For example: a band frequency can be non-required while the spectrum of oscillation types becomes one of the main parameters, as a working type appears the highest. New requirements are: a inter-beam distance and amplitude-phase distribution at an exciter output, etc.

A number of papers have been published studying the properties of space-developed electrodynamic systems of several types [2,3]. However, a detailed comparison of parameters (coupling resistance, maximum band, thermo-dissipation ability, etc.) of various systems has not been performed yet. There is almost no experimental data concerning such systems. The problems of the excitation of space-developed electrodynamic systems, power distribution, phasing, adjusting have not been solved. There is a lack of results concerning one of the main parameters: suppression of parasitic oscillation types. New systems appeared such as a spirally bent waveguide [2].

Studying the space-developed electrodynamic systems we use so-called coupling resistance [4]. For periodic electrodynamic systems:

$$R_n^o = \frac{L}{2c}\frac{|E_{zn}|^2}{k^2 W} = \frac{R_n}{n_{zp}} n_n^2,$$

where L is a period of a periodical structure in the direction of a beam motion, c is the velocity of light in vacuum, E_{zn} is a strength of the n-th space harmonic of a longitudinal electric field, k is the free-space wavenumber, W is the energy, stored in the period of the structure.
The generalized coupling resistance of an isolated resonator can be presented in the following form:

$$R^o = \frac{L}{2c}\frac{|E_z|^2}{k^2 W},$$

where now L is the resonator length, E_z is the longitudinal electric field strength, W is the energy, stored in the resonator.

It is not difficult to find an approximate value of R_n^o providing that the value of R^o is known.

The generalized coupling resistance is finite both inside pass bands and on pass band boundaries. It changes smoothly and insignificantly (for the principal space harmonic) inside the pass band, can be easily estimated (by using previously proved theorems [4]) in the band and on the band boundaries; can be easily estimated for space-developed systems.

Space-developed electrodynamic systems can be considered as ordinary periodic systems, reproduced in the transversal direction. When choosing an initial system it is important to understand which shape of the cross section is more preferable: circular, rectangular, square, etc. Keeping in mind the problem of the complete filling of the cross section it can be advisable to consider systems of triangular, hexagonal, parallelogram and other shapes.

It was rigorously proved [5] that the maximum value of the coupling resistance can be achieved in systems with a circular cross section (R^o=79.99 ohm). Systems with a rectangular cross section have the value of R^o=76.4 ohm. In systems with a rectangular cross section the value of R^o depends on ratio of transversal dimensions. In the whole, the effect of the cell shape on the value of R^o is insignificant, so the cell shape can be selected from some other reasons.

The inter-beam distance R is one of the major characteristics of the electrodynamic systems SDED, determining gun and cathode diameters and, if the cathode current density is fixed, perveance of each beam.

Possible approaches to the solution of the problem of increasing the distance between beams has been considered in [6], such as: use of phenomena on the critical frequency or neighbor frequencies, "skips" of one or several field maxima, use of the hollow resonators, segments of the transmission lines on the critical frequency, wave conversion phenomena.

Periodical ES developed in one of the transversal Cartesian directions or asimuthally, as well as structures with 'skips' of one or several maxima of the electric field have been studied in [7]. Ranges of values of the inter-beam distance to wavelength ratio (r'/λ), in which each of the indicated ES is the most efficient, have been obtained. It was shown that systems with "skips" can be more efficient than systems without "skips" at high values of r'/λ. Systems working on a critical frequency are efficient at small inter-beam distances.

Some increase of the value of the coupling resistance can be obtained when using systems with cells formed by step junction of two waveguides of different width [8]. A pair of real symmetrical second kind matrix equations with respect to the fields in one of partial regions has been obtained. It was shown that of one of the equations has better convergence of the truncated solution to the exact one.

It was proposed to use systems with inter-beam distance more than $\lambda/2$. Such systems are constructed from a number of sector resonators with replaced adjacent walls. An apex angle of sector resonators has been chosen from the condition that the total angle is equal to 2π. A phase

shift of fields in neighbor resonators is equal to π. Such systems are called super-multi-beam ones because a multibeam electron flow can be passed through each sector resonator.

Main characteristics of super-multi-beam systems have been studied. Some ways to suppress parasitic oscillation types have been proposed. Studies show that characteristics of super-multi-beam systems related to one beam are not worse than the characteristics of a chain of connected resonators (CCR). Super-multi-beam systems have greater dissipated powers, greater sizes, less sensitivity to manufacturing inaccuracies, smaller decaying coefficient, high coupling resistance, and large inter-beam distance. The spectrum of oscillation types of such a system is not denser than the one of CCR.

A compact system for separation, phasing and excitement of super-multi-beam systems has been proposed, devised and tested. An adjustment band is no less than 60% from the pass band providing that an immobile wave coefficient has a value more than 1.7.

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RESEARCH ON SECONDARY-EMISSION COLD-CATHODE MILLIMETER-WAVE MAGNETRONS

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The main principles of the development of the millimeter-wave band spatial-harmonic magnetrons with secondary-emissi. cold cathode are considered. The performances of the magnetrons developed at the Institute . Radio Astronomy are discussed.

1. INTRODUCTION

The progress in the development of millimeter wave radars depends essentially on the availability of efficient high power magnetrons. However, so far the creation of such magnetrons has encountered significant difficulties.

It is well known, that the dimensions of the magnetron interaction space vary in the direct proportion to the operation wavelength λ, and the dc magnetic field is proportional to λ^{-1}. Due to it the diameter value of an anode block of the *classic* magnetron is usually of about 1 mm, and the operating magnetic field can reach 20 kGs at short millimeter waves [1]. Usage of the *low field* operating mode gives possibility to decrease the magnetic field value and increase the anode diameter in approximately two times [2]. But, even in this case both anode and cathode of the device remain hardly loaded and, thus, the device is liable to quick breakdown. Because of this, the industrial production of short millimeter wavelength magnetrons is still problematic.

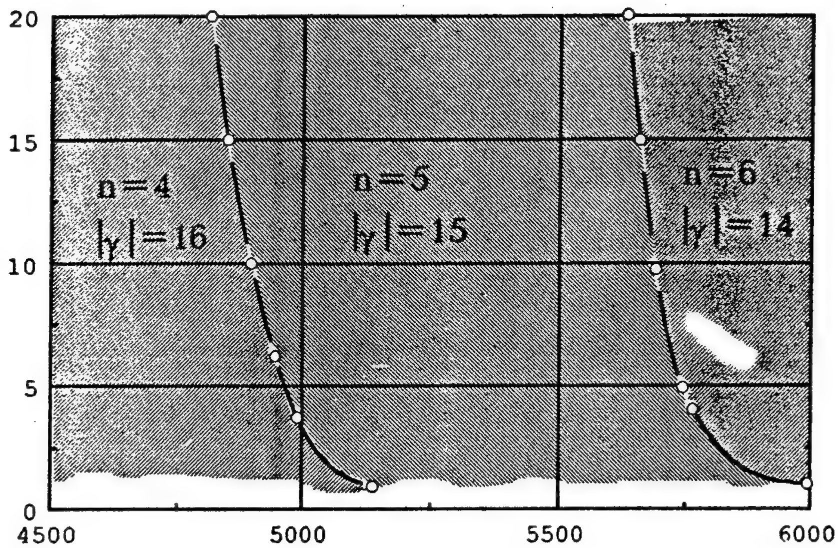
However, there are other approaches, which permit to get rid of these difficulties. At first, the classical π-mode should be rejected, and the $\pi/2$-mode or one close to it should be used as the working mode. In the latter case electrons interact with the first backward space. Secondly, standard thermonic magnetron cathodes should be replaced by cold secondary-emission cathodes. These two approaches give possibility to create a new generation of magnetrons suitable for the operation at frequencies up to 240 GHz.

2. THE SPATIAL HARMONIC MAGNETRON

The exploration of spatial harmonic magnetrons began in the USSR in 1945 by I.D.Truten's group, but the result was published only in 1975. The main results obtained can be found in [3]. Since this results may not be generally known let us mention the principal ones.

The main peculiarity of the considered magnetrons is using of operating mode with the phase shift of $\pi/2$ instead of π. The mode separation is sufficiently large in this part of dispersion characteristic and no means required to increase it. Since the delay factor is small for the basic spatial harmonic of this modes, the interaction of electrons is realized with the first backward harmonic. It turned out, that neighboring operating modes have materially different values of the dc magnetic field with a large enough values of the cathode current. This is illustrated in the plane of parameters (pulsed anode current, dc magnetic field) in fig 1 for magnetron with the number of

Pulsed anode current, A



Magnetic field, Gs

Fig. 1. Domains of generation of a 4-mm magnetron at $N = 20, \frac{r_k}{r_a} = 0.43$

resonators N=20; the cathode-anode ratio r_k/r_a=0,43. There are always intervals of the magnetic field variations where only a single mode is excited in a wide range of the anode current increasing. It means that there is possibility to utilize the emission ability of a cathode to a grate extent, or, in other words, the dynamic resistance of a magnetron ($R_d = \Delta U_a / \Delta I_a$) can be small enough. For example, the application of L-cathodes can provide the value of the dynamic resistance as little as 50Ω. In this case an effective mode separation by means of the magnetic field is easily realized. The boundary value of the magnetic field, when the transition from one operating mode to another occurs, is given by the following relationship:

$$B_t = \frac{21300}{\gamma\lambda\left(1-\sigma^{2^{|\gamma|/2}}\sqrt[2]{40000}\right)}, \quad (1)$$

where $\sigma = r_c/r_a$, $\gamma = n + mN$, λ is the wavelength, n is the mode number; m is the spatial harmonic number; N is the resonator number. It was found experimentally that preferable modes for a magnetron operation are those with n of $N/4+1$, $N/4$, and $N/4-1$. The application of the modes with the higher index value leads to the decrease of the magnetron efficiency, whereas the modes with the lower value of the index have a worse exciting conditions.

It is well known, that the modes with the numbers of $n \neq 0$, and $n \neq N/2$ in symmetrical anode blocks are double degenerated. This means that there are two possible distributions of r-f field for every mode with the phase shift between them of π /2. The presence of nonregularities in the resonator may lead to the simultaneous excitation of two oscillations with a small separation of the frequencies. One of this oscillations is strongly and the other is weakly loaded. It is naturally to suppose that the

unloaded component will be excited preferably as one having a higher Q. Apparently, it was the main reason for the rejection of the application of such modes by other magnetron research groups. However, the experimental results [3] indicate that even in the case of the application of the degenerated modes the power is transformed from the magnetron cavity to the load in a manner like that of the π-mode operation, and that the output characteristics of such magnetrons are reproduced well enough. The authors of [3] supposed that the loaded component has a lower frequency as compare to the unloaded component. To prove this they presented the experimental results of the investigation of the r-f pattern in a operating magnetron. However, a refined analysis of their results has shown that such conclusion is not always justified.

In particular, the measured frequency pulling of operating magnetrons is less than that calculated according the Q-value. Apparently, the excitation of the unloaded component takes place, but it gets coupled with the output due to the influence of the electron flow.

The authors of the paper [4] assumed that a traveling wave rather than standing one is excited in the case of the degenerated mode of the magnetron operation. This wave is always coupled with an output. This assumption agrees better with the experimental results.

Another feature of space-harmonic magnetrons is related with the fact that the operating slow wave excited near the anode resonators has a relatively large wavelength. Due to it a strong connection of the magnetron cavity with the end cavities take place. It lead to a nonreproductibility of the output magnetron parameters, what was observed on the earlier stage of the development of such magnetrons. To solve this problem special screens have been developed for shielding of the magnetron cavity. This improvement alone with other technical and technological solutions has culminated in the development of magnetrons with parameters given in Table I

Table I

Type of magnetron	classic		low field		space harmonic	
Wavelength, mm	3.3	2.5	3.9	2.8	3.1	2.2
Number of resonators	22	22	22	22	24	28
Anode diameter, mm	1.27	0.96	2.36	1.61	3.3	2.6
Magnetic field, kGs	25	>30	8.7	15	6.25	7.6
Anode voltage, kV	8-13	8-13	12-16	17-19	15	12
Pulsed power, kW	20	--	35	3.3	30	8
Efficiency, %	15	--	9.5	2.5	12	5.5
Life time, h	100	--	<10	<10	200	50

One can see essential advantages of space harmonic magnetrons. But, even increased, a short life time remains the main obstacle which prevent a wide practical application of those magnetrons. This drawback results from the using of high-temperature L-cathodes in this devices, which have low reliability due to the operation in a heavy conditions. Besides, an intensive sublimation takes place that naturally leads to spoiling of a magnetron resonator system and the Q-factor decay. The solution of this problem came from the application of second emission cold cathodes.

3. MILLIMETER-WAVE MAGNETRONS WITH SECONDARY EMISSION CATHODES

In order to improve the life time and reliability of millimeter-wave magnetrons and made them capable to work at a high duty factor the L-cathodes were replaced by cold secondary-emission cathodes (platinum foil on a copper core) with auxiliary

thermionic cathodes [5]. The cold cathode was placed inside the interaction space, whereas the auxiliary one was placed instead of an end cathode screen as shown in fig.2.

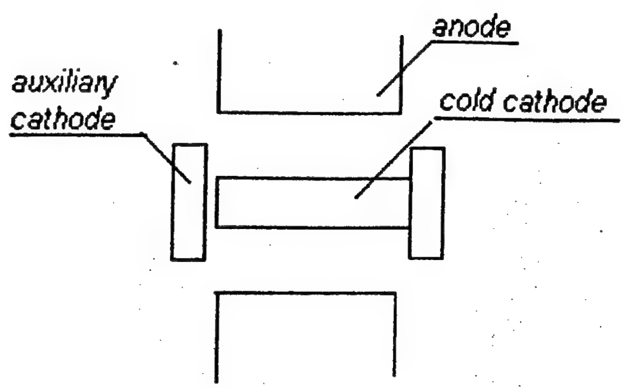


Fig. 2 Scheme of the magnetron with secondary-emission cathodes

The auxiliary cathode is used for the initiation of the secondary emission at the front edge of the anode voltage pulse. The experiments with centimeter wave magnetrons [6] has shown that in order to achieve a stable magnetron operation it is necessary to have secondary cathodes with the coefficient of the secondary emission δ more than 3. However, at present time there are no cathodes which both can provide such secondary emission and were able to work in the interaction space of millimeter- wave magnetron for a long time.

It seemed that millimeter magnetrons would demand a greater value of δ than centimeter ones, but it appears that this not the case. Let us mention results of Jepsen and Muller [7]. They found that the anode current is not changed if all geometric sizes are scaled simultaneously. Allowed input dc power is considerably lower for millimeter wave magnetrons because it is restricted by anode overheating. The operating anode current is also less, and due to it, for their operation a relatively low values of δ of pure metal, like platinum, appears to be sufficient. It was proved by our first experiments conducted in 1968. The output power level of 30 kW at the wavelength of 6,8 mm was reached. This power was essentially lower then that reported in [3]. Since the efficiency was the same, and it gave indication that the output power can be increased if we would manage to rise the dc prime power.

We found experimentally that the maximum secondary-emission anode current is determined by the following relation:

$$I_{am} = 0.1(\delta_m - 1) I_L \qquad (2)$$

where δ_m is the maximum of the coefficient of the secondary emission, I_L is Langmuirs's current for the cylindrical diode, which is equal

$$I_L = \frac{14{,}66 \cdot 10^{-6} U_a^{\frac{3}{2}} h_a}{r_a \beta^2(\sigma)} \tag{3}$$

where U_a is anode voltage, h_a is axis length of anode, r_a is anode radius, $\beta(\sigma) = \beta(r_c/r_a)$ is function of cathode /anode ratio.

Using expression (1) and (2), and taking into account that the maximum anode current can be obtained if the anode voltage reaches the critical value U_a given by

$$\mathrm{U_a} = 0{,}022 r_a^2 B^2 (1-\sigma^2)^2, \tag{4}$$

one can find the following expression for the maximum prime power:

$$P_{am} \approx \frac{1{,}05 \cdot 10^{-10} h_a (\delta_m - 1) r_a^4 B^5 (1-\sigma^2)^5}{\beta^2}. \tag{5}$$

Finally, substituting eq.(1) into eq.(5) we get

$$P_{am} \approx \frac{4{,}6 \cdot 10^{11} h_a (\delta_m - 1) r_a^4 (1-\sigma^2)^5}{\left(1-\sigma^2 \sqrt[|\gamma|]{40000}\right)^5 |\gamma|^5 \lambda^5 \beta^2}. \tag{6}$$

The prime power versus σ for the 6.8 mm space harmonic magnetron calculated according to eq.(6) is given in fig.2.

One can note, that the prime power increases rapidly with the σ rising. In our experiments the 120 kW power level was achieved by means of the increasing the σ-value from 0.49 to 0.58.

Varying the geometry of the interaction space we developed magnetrons with the power not less than that reported in [3], but we considerably improved the life time and duty factor of the magnetrons. Table II contains the main characteristics of short millimeter wave magnetrons developed according to this approach.

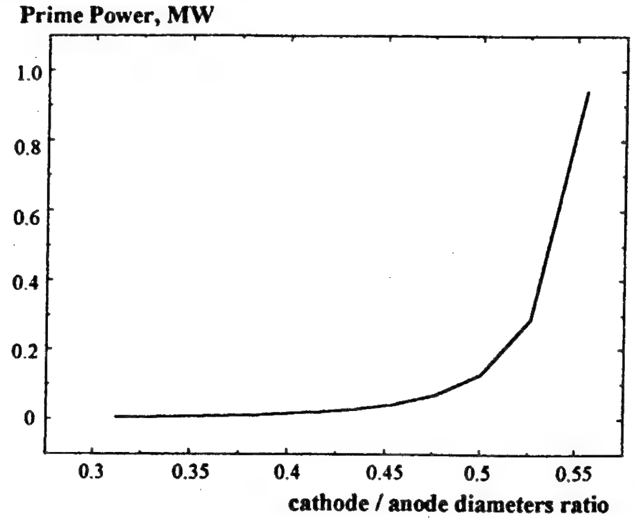


Fig.3. Prime power versus the ratio of cathode and anode diameters

Thus, the high power magnetrons with the peak power of 20 kW at the 3 mm wave band and the 10 kW at the 2 mm are available. We have developed also mechanically tuning magnetrons with the tuning range of 1.5%, noted in the table as MT310/5-2 and MT220/3-2. Other direction of our activity is related with development of miniature low voltage magnetrons. For example, the magnetron M310/0.5-1 with the weight of 300 gr. has pulsed power 0.5 kW at 95 GHz. Preliminary results also indicate the possibility of increasing the power up to 1 kW.

Table II

Type	Wave-length (mm)	Peak power (kW)	Average power (W)	Pulse duration (μs)	Peak voltage (kV)	Weigh t(kg)	Life time (hs)	Cooling
M310/20	3.1	20	20	0.1	18	2.0	500	Water
MT310/5-2	3.1	5	5	0.3	15	1.7	1000	Forced-air
M310/5-3	3.1	5	40	1.0	12	2.0	1000	Water
M310/0.5-1	3.1	0.5	1.0	0.5	6.5	0.3	2000	Forced-air
M220/10	2.2	10	10	0. 07	15	1.7	200	Forced-air
M220/3-2	2.2	2.5	3	0.1	13	1.7	200	Forced-air

4. CONCLUSION

The data presented in this paper demonstrate that the application of the spatial harmonic interaction mechanism along with the secondary emission could cathodes allows to create millimeter-wave magnetrons which are attractive for practical purposes. We are foreseeing a number of areas of their applications including various types of mobile radars, guidance systems, security system and so on.

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Vacuum Sources of Millimeter Waves Based on Cyclotron Frequency Harmonics

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Abstract. The results of the study and design of gyrodevices based on the higher (n>5) harmonics of cyclotron frequency are presented. The greater interest has been drawn to the study of gyroresonant devices with the peniotron mechanism of interaction. The peniotron is a new type of the vacuum sources of electromagnetic radiation providing the high power of output signal and high efficiency in the millimeter wave range. I was shown that effective small-sized generators and amplifiers of the high frequency wave ranges with the peniotron interaction mechanism could occupy a niche between classical radiation sources and gyrotrons.

1. Introduction

Gyrodevices based on the higher harmonics of cyclotron frequency with gyrotron and peniotron mechanisms of interaction between electrons and waves have been intensively studied from the end of the 70s. A number of papers have been devoted to theoretical investigations of the energy characteristics of gyrotrons based on the higher gyroharmonics [1-5]. A great quantity of papers dealt with the results of studies of devices with peniotron mechanism based on the higher gyroharmonics [6-28]. Thus in this communication our interest was centered on such devices.

Peniotron is one of few microwave devices having the value of estimated efficiency exceeding 90%. Here almost ideal mechanism of electron-wave interaction is realized. Due to the phase sorting under the condition $n=m-1$ (n is the number of the synchronous harmonics of cyclotron frequency, m is the number of azimuthal variations of the field), all the electrons of a tubular thin-walled monocoil electron flow transfer the energy to the electromagnetic wave with an equal average value over the period of revolution, independently on the phase of entering the interaction space. This provides a high efficiency of the device. Recently a high efficiency of peniotron sources of electromagnetic radiation has been proved both theoretically and experimentally [6-21, 28].

Peniotron is an electrovacuum device for amplification or generation of high frequency electromagnetic oscillations. The first studies of interactions of rotating with a helical trajectory current filament and rotating in the same direction the electromagnetic field component with the number of azimuthal variations equal to the gyro-resonance order plus one (such an interaction is now called peniotron one) have been published in 1962 in theoretical works [6,7]. In [6] a low-signal interaction of the ring electron flow with the field of rolled up corrugated waveguide has been studied under the condition that an unperturbed electron trajectories were closed, and the 2nd order dispersion equation has been obtained. This equation shows that the field can be self-excited in the appropriate resonator.

In [7], a low-signal theory of the amplifying device with a coiled electron beam moving inside a rectangular waveguide with longitudinal ridges on its wider walls has been developed. Such a device has been experimentally constructed and the results of its study are described in [8]. A cylindrical beam with the 20mA current has been formed by the Piers gun and has been ejected into the interaction space with the accelerating voltage about 40 kV at the angle of 60° to the direction of the longitudinal magnetic field and the waveguide axis. In this case the amplification of the signal on the 2nd harmonic of the cyclotron frequency has been observed.

The studies of gyrodevices with the peniotron interaction mechanism are currently being held in Japan, USA, Russia, Ukraine, Belarus and China. The most of published papers deal with the theoretical investigation of the peniotron interaction [6,9-12, 14-24].

The electron optical systems forming the monocoil (high-orbit) tubular electron flow are usually used in gyrodevices based on the higher gyroharmonics of cyclotron frequency.

2. Adiabatic electron optical system

The studies of the characteristics of the vacuum sources of mm waves with gyrotron and peniotron electron-wave interaction mechanisms based on the higher harmonics of cyclotron frequency show that the energy characteristics in both generating and amplifying regimes strongly depend on the electron-optical system parameters. This system forms a monocoil (rotating with the cyclotron frequency around the system axis) tubular electron flow (EF) with a high level (> 70%) of rotational energy. The monocoil EF's have not been studied enough but draw the attention due to using them in gyrodevices based on the higher harmonics.

In this communication the results of a computer modeling and experimental design of the triode scheme of EOS forming monocoil tubular EF for a pulse peniotron, called difratron, working on the resonance frequency 100 GHz on the 10th cyclotron harmonic [27].

According to the Bush theorem ($\theta = \varpi_0(1-\frac{\psi_i}{\psi})$) the rotation of a tubular EF with the cyclotron frequency $\omega_{\tilde{\pi}} = \eta B$ about the system axes is realized when the flows of the magnetic field displacement on the cathode ψ_i and in the interaction space $\psi(\psi_i = -\psi)$ have equal values and opposite directions. Neglecting the radial component of the electron velocity (v_r=0) and taking into account that the angular electron velocity is $v_\varphi = D/2\omega_c$, one can obtain the following relationship: $D_k^2 = 4.55\cdot 10^{-11}\cdot\frac{UW_\varphi}{BB_k}$ from the energy conservation low: $2\eta U = v_z^2 + v_\varphi^2$. This relationship connects the average emitter diameter (D_k), average diameter of the flow in the interaction space (D), magnetic field displacement on the cathode (B_k) and in the interaction space (B), the interaction space potential (U) and the relative value of the flow rotational energy ($W_\varphi = \frac{v_\varphi^2}{v_z^2+v_\varphi^2}$). The average (equilibrium) flow diameter in the interaction space can be described with the well-known formula: $D = D_k\left(\frac{B_k}{B}\right)^{1/2}$ in the presence of the intensive field on the cathode. To provide a small dispersion of the electron rotational energy and a required current density on the cathode, the ring emitter width has to be significantly smaller than the average cathode diameter ($\Delta/D_k \ll 1$) [27].

Presented analytical relationships are the basic criteria to choose a triode gun forming a high-orbital tubular electron flow with the given level of rotational energy. Realization of these criteria is achieved by a subsequent design of EOS and MFS, to adjust the gun with the magnetic field in the interaction space and hence minimize the radial pulses of the flow.

3. The gyrotron based on the higher gyroharmonics

To provide the gyrotron operation in mm and sub-mm wave ranges, superconducting magnets are needed. They can be used while working in stationary conditions but in on-board radiosystems it is advisable to use gyrotrons with permanent magnets. That is why the design of gyrotron based on the higher gyroharmonics of cyclotron frequency is a very actual task. In gyrotrons the intensity of interaction of electrons with an electromagnetic wave on the harmonics of cyclotron frequency is determined by nonhomogeneity of a high-frequency field on the l'Armour orbit. As a result, the increase of the harmonic number and decrease of the accelerating voltage cause the increase of the starting currents.

The possibility of design of efficiently working gyrotron on the 2nd harmonic with EOS forming a policoil tubular electron flow has been first demonstrated experimentally in 1963 [1]. In the regime of continuous generation, 190 W power has been obtained on the wavelength λ=12 mm. Further works have been devoted to the experimental and theoretical study of classical gyrotrons to increase their output power, efficiency, and working frequency.

It appeared that gyrotrons on the higher harmonics theoretically could have efficiency at the level of the best gyrotrons based on the first harmonic [1]. Major factors obstructing the increase of classical gyrotrons frequency and power are the oscillation competition and the increase of omical

losses in a resonator. At the same time the decrease of magnetic field simplifies significantly the magnetic system construction and for existing magnetic fields shortens the working wavelength.

One of the approaches to design the gyrodevices on the higher gyroharmonics of cyclotron frequency is to use a high-orbit monocoil electron flow which moves inside the electrodynamical system similar to magnetron waveguide [2-6, 13,15-21,28]. Passing one cyclotron orbit, electrons undergo the action of n field variations, n being the number of the periods along the magnetron waveguide wall. In this case the working frequency $\varpi = n\varpi_c$, where ϖ_c is the cyclotron frequency.

This experimental result was first registered in the experiments with intensive relativistic electron beams [29]. In the New York Politechnical University a tube with a magnetron waveguide on the 16th cyclotron harmonic with magnetic field 0.036 T and working voltage 28.5 kV provided the output power of 3.21 kV with efficiency 11% at the frequency of 156 GHz.

Studies of gyrotron based on the higher harmonics of cyclotron frequency using quasi-optical resonators of the Fabri-Pero type are being carried out. The radiation with the 1 mm wavelength has been observed on the 9th cyclotron harmonic with the working magnetic field 1.4 T.

4. High-orbit peniotron with through gyro-resonance

In the Institute of Radiophysics and Electronics of NASU, the scheme of high-orbit peniotron with through gyro-resonance has been developed. It consists of: 1) magnetron waveguide (to select the mode with a required azimuthal number), 2) peniotron interaction mechanism (to provide the equal status of all electrons of the flow), 3) the through gyro-resonance regime (to obtain a high efficiency). The high efficiency of a single electron, the same as of all electrons, can be reached by forming a smooth profile of the interaction space providing the through resonance regime. A device having all the three mentioned features is called "peniomagnetron" [15]. Peniomagnetron with a profiled magnetostatic field is an effective amplifier of millimeter waves. The magnetic system of peniomagnetron based on the higher gyroharmonics has a small size and mass. The working magnetic field of 3-mm range peniomagnetron on the 5-10th gyroharmonic has a value of 0.3-0.8 T.

An efficient operation of peniomagnetron with great orders n of the gyro-resonance and great azimuthal numbers $m=n+1$ is possible only at high radii of electron orbits, reaching a zone of intensive microwave field. The values of radii are determined by the following condition of the gyro-resonance:

$$r_1 = \frac{n \cdot v_t}{\omega(1 - v_z / v_\Phi)} \tag{1}$$

where v_z, v_t are the longitudinal and transversal velocities of a particle, v_Φ, $\omega = 2\pi c\lambda$ are the phase speed and angle frequency of the traveling wave, λ and c are the wavelength and velocity of light in vacuum. From (1) it follows that there are two ways to obtain high values of radius r_l : to increase a relative value of the longitudinal velocity v_z/v_Φ or to increase the absolute value of the transversal velocity v_t. The former can be easily realized in the non-relativistic case when using an axial delay of waves. The latter can be realized only for relativistic electron flows.

4.1 Peniomagnetron with axially delayed wave

The efficiency of a magneto-profiled peniomagnetron with an axially delayed H_{ml}- wave rotating in the magnetron waveguide and interacting with an electron monotube of a great diameter on the high gyro-resonance order has been studied. The effect of the space charge forces has not been taken into account. In this case an equal status of all particles of the electron flow of the peniotron-amplifier allows defining its energy characteristics of interaction providing that the energy characteristics of a single electron are known. The electron motion in the electromagnetic field of the axially delayed H_{ml}- wave is described by the system of differential equations [16]. The problem has been solved by using the Bogolubov-Mitropolksy method combined with the method of frequency separation. Below a sample calculation of the amplifier parameters is presented. Beam: working voltage U_p= 10kV, initial pitch-angle ψ_o=60°, working current I_p=0.25A, initial radius r_o=1.83 mm, the number of coils M=24.5. The magnetron waveguide with an axially delayed wave: mode $H_{11,1}$, phase velocity normalized on the

velocity of light β_{Φ}^{opt}=0.383, wavelength λ=5 mm, channel radius a=2 mm, input signal power P_o=1.3W, excitation parameter u=10^5, output signal power P_o=1.31W. The regime: continuous, gyro-resonance order n=10, efficiency 51%, initial displacement of the magnetic field B_o=0.16 T, final displacement B_o=0.185 T.

4.2 Relativistic high-orbit peniomagnetron

The interaction of electrons of a high-orbit flow with the field of non-delayed in the axial direction H_{ml}-wave rotating in the magnetron waveguide has been studied. According to formula (1) the gyro-resonance regime of particle motion in this case can take place when the transversal electron velocity has relativistic values. Below the values of calculated parameters of the relativistic peniomagnetron working in the regime of though gyro-resonance on the 10^{th} cyclotron harmonic are presented. Beam: γ_i=4, ψ_i=55°, initial diameter 2.5 mm, the number of coils 10. The waveguide: mode $H_{11,1}$, β_{Φ}=1.122, E_{cm}= 250MV/m, wavelength λ=0.5 mm, magnetron tube length 10 cm, inner diameter 4.51 cm. The regime: n=10, efficiency η= [illegible]%, B_{oi}=4.33 T, $\delta \geq$ 0.33. When the beam current is equal to 11kA the calculated high-frequency power is 1GW.

Thus the profiling of gyrodevice parameters by using the principle of the trough gyro-resonance allows combining the multiple frequency gain (working on the higher harmonics of the cyclotron frequency) with the relativistic energy of the input flow and high electron efficiency, at reasonable static and microwave field values and acceptable sizes of the interaction space.

5. The work of the peniotrons in the resonance regime

In 1987 and 1988 it was shown [30-32] that a working regime with an extremely high frequency: an autoresonance regime, can be realized in the peniotron [25,26]. The autoresonance regime is realized in the peniotron based on the higher harmonics of the cyclotron frequency. This allows considering the sources of millimeter waves with the peniotron mechanism of the electron-wave interaction as one of the most prospective amplifiers and generators of the electromagnetic radiation of average and high power. When designing the resonance peniotron working in the autoresonance regime, some problems arise due to the fact that the process of the energy exchange between the electrons and the passing wave is significantly perturbed because of the particle de-phasing due to the gyrotron interaction with a counterwave. That is why the peniotrons-amplifiers, in which the amplitude of a counterwave can be decreased by an optimum adjusting of the output system to a load and decreasing a reflection level, are preferable for the further development. In this communication the possibility of the design of the efficient autoresonance peniotron-generator with a neutralized destabilizing effect of a counterwave is shown.

In the design of a peniotron using EOS that provides the channeling of wave with a phase velosity equal to the free-space velocity of light (doubly periodic magnetron waveguide or multiply connected electrodynamic system), magnetic profiling is not required because in this case the trough resonance regime is realized in the homogeneous magnetic field due to the autoresonance effect [25,26]. Autoresonance peniotron interaction on the harmonics of the cyclotron frequency is characterized by the feature that the electrons of the current monotube loose the energy of both the longitudinal and transversal motion. A phase grouping of electrons is not required.

5.1 The study of autoresonance peniotrons-generators of millimeter and sub-millimeter waves

Nonlinear analytical theory of the autoresonance peniotrons-generators has been developed. Electrodynamic system of such a device can be realized as a multiply connected waveguide or weakly diaphragmed magnetron waveguide providing the channeling of TEM- or quasi-TEM-waves. The theory has been developed with the assumption of a thin rotating current monotube without a dispersion of electron locations and velocities. The effect of the space charge forces has not been taken into account. Due to the relative simplicity of the design and high values of the autoresonance

peniotrons-generators efficiency in mm and sub-mm wave ranges, they can be considered as potentially efficient sources of the high frequency radiation.

5.2 The study of autoresonance peniotrons-amplifiers of millimeter and sub-millimeter waves

Nonlinear analytical theory of the autoresonance peniotrons-amplifiers has been developed. The stability of the autoresonance peniotrons-amplifier operation has been considered taking into account the dissipation of electron locations and velocities, nonhomogeneity of the magnetostatic field, and the effect of the counterwave [19]. Non-averaged equations of motion of the current monotube in the field of rotating TEM-wave with a constant amplitude have been solved numerically. It was graphically illustrated that autoresonance peniotrons are most sensitive to the dispersion of particle pitch-angle values and magnetic field nonhomogeneity. However they are essentially stable to such disturbing factors as the dispersion of total velocities and non-coaxiality of the monospiral flow and the interactior space channel. In particular, while working on the fifth gyroharmonic, the amplifier efficiency is . creasing from 50% with negligible dispersions and nonhomogeneities to 25% with the dispersion of total electron velocities about 33%, pitch-angle 10%, magnetostatic field nonhomogeneity 1.4%, and non-coaxiality of fly-in up to 12.7% from the initial gyroradius. The amplifier operation band is about 1.5%. To study the bandwidth characteristics of autoresonance peniotrons-amplifiers, the problem equations have been solved numerically. The amplification band at the efficiency halfvalue reaches several percent. To increase the band in M times one should increase the device current in M^2 times. If the current value is small the increase of the number of the coils up to 12-15 results in the increase of the device efficiency. The calculation of the energy and band characteristics of the autoresonance peniotron-amplifier, performed taking into account the influence of the space charge force, confirms that the Coulomb forces lead to the efficiency decrease when the number of cyclotron harmonic and the current, of the monocoil flow are increasing. To maximize the amplification coefficient and efficiency within the given frequency band and with given value of the amplifier working current it is necessary to optimize the interaction space length and the value of accelerating voltage.

Conclusions

Small-size gyrodevices with gyrotron and peniotron interaction mechanism can occupy a niche between the classical vacuum sources of millimeter and sub-millimeter waves and gyrotrons. With the diameter of the electron flow channel of the same order as the wavelength of the output signal, the gyrotrons and peniotrons based on the higher harmonics of the cyclotron frequency can potentially provide the high efficiency and output power, and smaller size, mass and working voltage.

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OPTIMIZATION OF MAGNETRON CAVITY FOR MICROWAVE OVEN

Slow-wave structure, which using in electron devices, is intended to create conditions when propagating electromagnetic wave can the most intensive to interact with moving electron beam.

It is found experimentally that the best conditions of electron interaction with field define in those causes when electron velocity and phase wave velocity close one to other.

The principal part of slow-wave structure is to accumulate the high-frequency energy and fixation of oscillation frequency. The slow-wave structure may become like filtre with narrow bandpass that from all frequencies connecting with electron beam discriminate definite one [1].

The most important characteristics of slow-wave structure are its dispersion characteristic, i.e. function of phase velocity propagating wave along this structure versus frequency.

Using dispersion characteristic it can estimate value of frequency separation between oscillation mode, possible width of magnetron's linear tuning, partial influence of structure constructive parameter to mode frequency separation and value of tuning where it is expected stability operation of magnetron.

The design and the simulation of characteristics of magnetron's slow-wave structure carry out using two essentially different methods:

- field theory method, which is based by solution of Maxwell's equations for composite cavity. It is calculated resonance frequency spectrum and components of electromagnetic field in magnetron's interaction space;
- dual circuit method, which is based by solution of Kirchhoff's equations for made circuit or resonators.

Dual circuit method isn't allowed to calculate the resonance frequencies to a high precision. This method is allowed only qualitative representation about frequency spectrum, that is about fundamental (first) resonance group.

Above-mentioned resulting the calculations of dispersion characteristics was used by field theory.

The investigation of magnetron's slow-wave structure is assumed to define the possible configuration of high-frequency in interaction space, to find frequency spectrum and to determine function versus geometry parameters of slow-wave structure [1].

Here we limit only determination of own frequency spectrum versus geometry parameters of slow-wave structure. To find such characteristic of slow-wave structure, using field theory, it is necessary to solution of resonance equation, which in general cause it can written

$$Yn + Yr + Ya = 0,$$

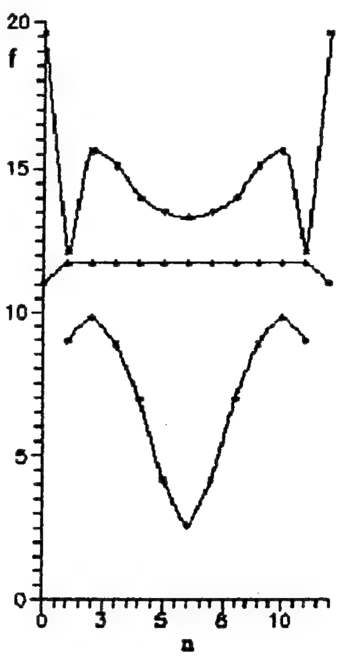
where Yn - interaction space admittance;
Yr - cavity admittance;
Ya - complementary admittance, using that if it is necessary to allow admittance of

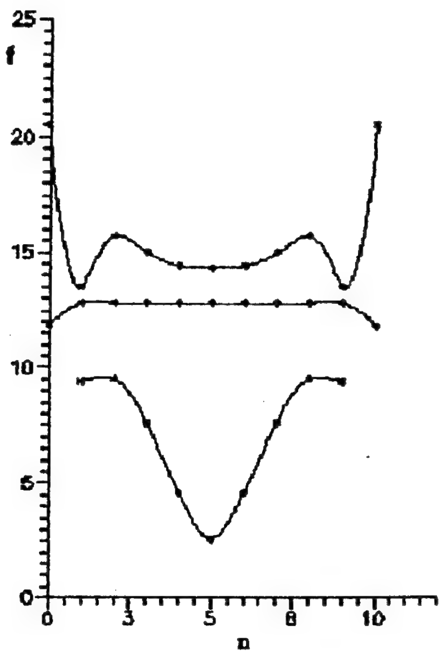
rings, outer resonator ect.

Roots of above-mentioned equation for different segments' pair define dispersion characteristic of magnetron slow-wave structure.

Every addend for resonance equation has enough cumbrous entry, which is shown in [1,2]. Resonance equation was solved for different cavity assembly.

The dispersion characteristic which was calculated by equation for magnetron for microwave ovens with N = 12 and N = 10 is shown in figure.





Dispersoin characteristics of magnetrons

a - 12 cavities; b - 10 cavities

The comparison between the dispersion characteristics finding theoretically and the experimental results allows the discrepancy no more 8 %. The calculation of dispersion characteristics by field theory is profitably differ from the solution to find by using finite element method which describe in [3]. The comparative results are shown in the table.

Method	Finite element		Field theory	Experiment
	E element	H element		
Frequency (GHz):	2478	2482	2501	2493
CPU time (s)	374	377	7	-------

However programs which are used to calculations of magnetron dispersion characteristics are enough cumbrous and not convenient for usual users. Thus to operate the usual users with these programs it was created system allowing to calculate the dispersion characteristics of slow-wave structures with any cavity configuration in dialogue mode.
Computer-aided design of magnetron slow-wave structure consists of two independent subsystems:

- the dialogue subsystem, which during the operation, is defined of slow-wave structure configuration, interesting resonance group etc. Proceeding from this there are is chosen necessary program units in
calculation system part. The dialog. subsystem is written in procedure language REXX using DMS/CMS system for operation systems such as VM/SP, OS/2, PC DOS (MS DOS);.
- the calculation subsystem, which during the operation from earlier defined slow-wave structure configuration, is chosen from object program library the units which is necessary to calculate the dispersion characteristic for chosen slow-wave structure configuration. The calculation subsystem is written in FORTRAN language using object unit library.

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HIGHVACUUM INJECTOR OF THE LARGE TRANSVERSE THRASHING OF THE ELECTRONIC WISP

M.A. Krasnogolovetz

The electronic cannon is the main knot, which define more impotant parameters VHF gear of different nomination [1 - 2]. So, for example, the electronic cannon of the large transverse thrashing applicate for supporting dependent gaseous discharge in the quantum generator of the large power.

During treatment of the injector of electrons was setting the undertaking of the creation of optimum construction of the cathode knot with the development working surface of the emitter.

The developing injector must to have the quadrature form of the wisp and to possess disproportionate of distribution of the density of current of the emission, don't exeed 10%, and the current of wisp is inserting either in the atmosphere or in the active enveronment with a division, equal 760 mm mer.c..

In the work the different methods of the heating emission materials of the cathode wich the development surface were researched. The main attention is allot to proportional heating all the surface of the emitter. The possibility of creation the lirectly heated cellular thermocathode with the development working surface from clean refractory emission metallic materials are scrutinized.

The highvacuum greatprecise injector of electrons has the follow tecnical parameters:

- **working vacuum volume, cm - $8 \cdot 10$;**
- **surplus thrust of the working gas, mm mer.c. - $2 \cdot 10^{-6}$;**
- **tension of the impulse sourse highvoltnutrition, kV - 300;**
- **protraction of the impulse of injection MS - 30;**
- **dimentions of the injecting electronic wisp cm x cm - 15 x 15;**
- **summed current of electronic wisp, Δ - ≤100;**
- **disproportionate of density of current of electronic wisp on the transverse thrrashing less, % - 12;**
- **summed using power in the wisp, kWT $\approx 3 \cdot 10^3$;**
- **energy of electronic wisp, Dj $\approx 10^3$;**
- **friquency of getting impulse, HZ - 1;**
- **dimentions cm x cm x cm - 54 x 70 x 90;**

The results of the convey treatments can using in the scientific recearches in the atomic physics, and for construction and execute the apparatuses of accelerater and genereter technique.

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IMPROVEMENT OF OUTPUT PERFORMANCE FOR MAGNETRONS FOR MICROWAVE OVEN

Domestic microwave ovens was manufactured since middle of 60-s. During these years with improvement of ovens it was improved the magnetrons which are main element of such oven. To improvement of magnetrons the emphasis was placed on stability, efficiency, improvement of cavity resonator. Before to exchange the cavity resonator it must assured other complex performances of magnetrons don't make worse. We have had some method to estimate these performances.

Here the estimate of operating performances of magnetrons for microwave ovens will propose by modified Kovalenko:

$$I_a = \sqrt{\frac{\left(U_a\left(U_a + \frac{\beta}{\left(1+\gamma/B\right)^2} - \alpha B\right)\right)^3}{\delta^3 \varepsilon B^2}},$$

where I_a, U_a - are anode current and pressure, responsibly;

B - magnetic intensity;

$\alpha = \frac{\pi}{N} f d_a^2 \left(1-\sigma^2\right);$

N - number of cavity;

f - oscillation frequency;

d_a - anode diameter;

d_κ - cathode diameter;

$\sigma = d_\kappa / d_a;$

$\beta = \frac{4}{\eta} \frac{\pi^2 d_a^2}{N^2} f^2,$

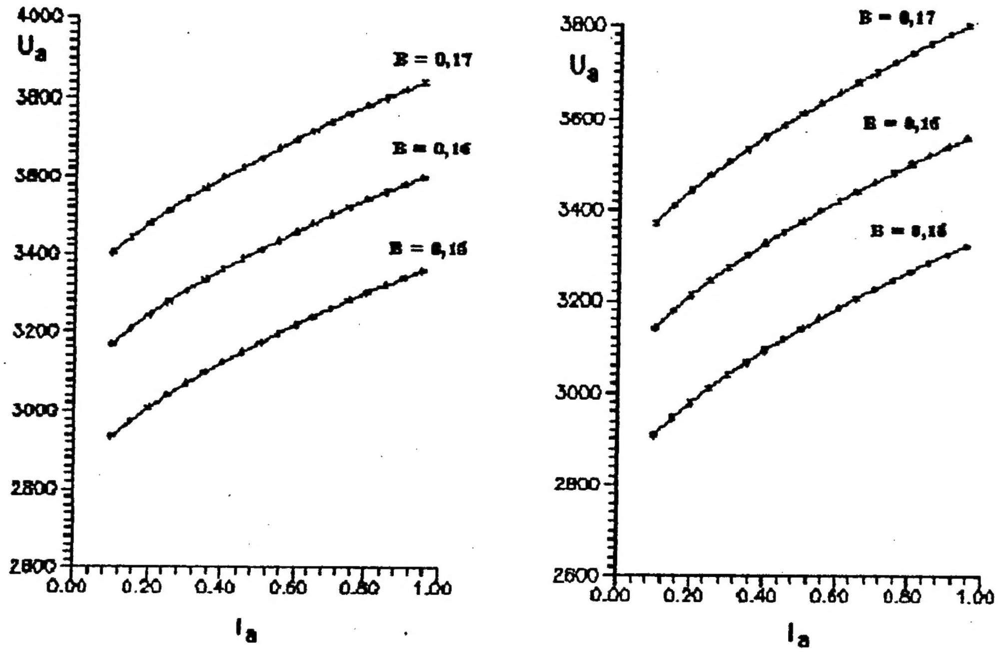
$\gamma = \frac{4\pi}{\eta N} f;$

$\delta = \frac{d_a}{\pi}(1-\sigma)^3;$

$\varepsilon = \frac{2d_a}{\pi^2} \frac{N^2}{h^2(1-\sigma)};$

h - anode height.

Using this expression it was estimated magnetrons which manufactured country industry and modifies ones with reduced number of cavities. In figure it is shown volt-ampere performances of magnetrons with 12 and 10 cavities for microwave ovens.



a b

Volt-ampere performances of magnetrons for microwave ovens

a - 12 cavity; b - 10 cavity

Here we saw the reducing number of cavity can't degrade integral performances of magnetrons. After determination electrical parameters using integral performances we can determine cavity performances of magnetrons.

Computer-aided design integral performances of magnetron consists of two independent subsystems:

- the dialogue subsystem, which during the operation, is defined of slow-wave structure configuration, interesting resonance group etc. Proceeding from this there are is chosen necessary program units in calculation system part. The dialogue subsystem is written in procedure language REXX using DMS/CMS system for operation systems such as VM/SP, OS/2, PC DOS (MS DOS);
- the calculation subsystem, which during the operation from earlier defined geometry configuration, is chosen from object program library the units which is necessary to calculate the integral performances for chosen geometry configuration and electrical and magnetic fields. The calculation subsystem is written in FORTRAN language using object unit library.